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Sensitivity of tracer transport in ECHAM5

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Sensitivity of tracer transport to model resolution, forcing data and tracer lifetime in the general circulation model ECHAM5

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Abstract

The transport of tracers in the general circulation model ECHAM5 is analysed using 9 independent idealized tracers with constant lifetimes released in different altitude regions of the atmosphere. The source regions were split into the tropics, Northern and Southern Hemisphere. The dependency of tracer transport on model resolution is tested in the resolutions T21L19, T42L19, T42L31, T63L31 and T106L31, by employing tracers with a globally uniform lifetime of 5 months. Each of the experiments uses prescribed sea surface temperatures and sea ice fields of the 1990s. The influence of meteorology and tracer lifetimes were tested by performing additional experiments in the T63L31 resolution, by nudging ECHAM5 towards the European Centre for Medium Range Weather Forecast 40 years re-analysis data (ERA40), and by using tracer lifetimes of 0.5 and 50 months, respectively. The transport of tracers is faster in the finer resolution models and is mostly dependent on the number of vertical levels. We found a decrease in the inter-hemispheric transport of tracers with source region at the surface or the tropopause in the coarse resolution models due to increasing recirculation within the source region and vertical mixing. However, a coarse model resolution leads to enhanced inter-hemispheric transport in the stratosphere. The use of ERA40 data only slightly affects the inter-hemispheric transport of surface and tropopause tracers, whereas it increases the inter-hemispheric and vertical transport in the stratosphere by up to 100% and by a factor of 2.5, respectively. The inter-hemispheric transport time was deduced from simulations with tracers of infinite lifetime and source regions at the surface in the Northern and Southern Hemisphere. Again, the transport was found to be faster for models with higher vertical resolution. We find inter-hemispheric transport times of about 7 to 9 months which are lower than the values reported in the literature, based for example on ^{85}Kr observations.

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1 Introduction

Transport plays a crucial role in determining the distribution of gas-phase and particulate trace constituents in the atmosphere. Numerical models are an essential tool for simulating atmospheric transport and distribution of trace species. However, the ability of a model to simulate the observed distributions of these trace species is largely dependent on its capability to reproduce the transport and mixing of the real atmosphere. Gurney et al. (2002, 2003) show that differences in model transport are a significant source of uncertainty. Hall et al. (1999) concluded that transport inaccuracies significantly affect the simulation of important long-lived trace species in the lower stratosphere. Model resolution also plays an important role. Genthon and Armengaud (1995) hinted that model spatial resolution is an important factor in the simulation of the distribution of ^{222}Rn , while Austin et al. (1997) and Wild and Prather (2006) demonstrated the influence of model resolution on the simulation of ozone distribution in the stratosphere and the troposphere, respectively.

Idealized tracers have previously been employed to investigate specific features of atmospheric transport, for example Gray (2003) used passive tracers to study the influence of convection on stratosphere – troposphere exchange of air. Also by comparing the results from different model resolutions, idealized tracers may explain some of the discrepancies observed in the distribution or seasonality of atmospheric trace species in different models (e.g. Genthon and Armengaud, 1995; Jacob et al., 1997; Denning et al., 1999; Stevenson et al., 2006).

In a special issue of the Journal of Climate, titled “Climate Models at the Max Planck Institute for Meteorology (MPI-M)” (Vol. 19, Issue 16, August 2006), the influence of model resolution on simulated climate in the ECHAM5 (Roeckner et al., 2003) general circulation model (GCM) was presented by Roeckner et al. (2006). The evaluation of the hydrological cycle in the model is presented by Hagemann et al. (2006). The snow cover and surface albedo were assessed in Roesch and Roeckner (2006), while Wild and Roeckner (2006) discussed the radiative fluxes in the model. This study ex-

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tends the assessment of the ECHAM5 model by testing the sensitivity of the transport of tracers “emitted” at 9 different locations in the model, in order to answer three major questions: (1) How sensitive is the transport of tracers to model resolution? (2) How does a change in forcing meteorology and tracer lifetime affect tracer transport? (3) What are the characteristic time scale for inter-hemispheric transport?

A brief description of the ECHAM5 model and the details of the model set-up are given in Sect. 2. The results are presented in Sect. 3 through 5. These include the analysis of the global characteristics of tracer transport in Sect. 3, the discussion of the transport from the source regions into various receptor regions in Sect. 4, and the calculation of the inter-hemispheric transport time in Sect. 5. The summary of our findings is presented in Sect. 6.

2 Model description

2.1 The ECHAM5 general circulation model

The atmospheric general circulation model ECHAM5 is the fifth-generation climate model developed at the Max Planck Institute for Meteorology, evolving originally from the model of the European Centre for Medium-range Weather Forecast (ECMWF) (Simmons et al., 1989). The dynamical core of ECHAM5 solves prognostic equations for vorticity, divergence, logarithm of surface pressure and temperature, which are expressed in the horizontal by spectral coefficients. The model uses a semi-implicit leapfrog time integration scheme (Robert et al., 1972; Robert, 1981, 1982) and a special time filter (Asselin, 1972). The vertical axis uses a hybrid terrain-following sigma-pressure coordinate system and finite-difference scheme citsimbur81. The finite-difference scheme is implemented such that energy and angular momentum are conserved. Water vapour, cloud liquid water, cloud ice and trace components are transported with a flux form semi-Lagrangian transport scheme (Lin and Rood, 1996) on a Gaussian grid (Arakawa C-grid, Mesinger and Arakawa, 1976).

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ECHAM5 contains a microphysical cloud scheme (Lohmann and Roeckner, 1996) with prognostic equations for cloud liquid water and ice. Cloud cover is predicted with a prognostic-statistical scheme solving equations for the distribution moments of total water (Tompkins, 2002). Convective clouds and convective transport are based on the mass-flux scheme of Tiedtke (1989) with modifications based on Nordeng (1994). A detailed model description is given in Roeckner et al. (2003). The model successfully participated in recent scenario experiments for the fourth assessment report of the Intergovernmental Panel on Climate Change.

ECHAM5 can be run as a coupled ocean-atmosphere model, or with forced boundaries from prescribed sea surface temperatures and sea ice cover fields. In addition, a Newtonian relaxation technique, also termed “nudging” (Hoke and Anthes, 1976; Jeuken et al., 1996) can be applied in order to simulate real weather episodes. The atmospheric forcing (surface pressure, temperature, vorticity, and divergence) is then obtained from numerical weather prediction models with data assimilation, e.g. the ECMWF 40-years re-analysis data (ERA40, Simmons and Gibson, 2000).

ECHAM5 contains a flexible software structure for defining atmospheric tracers. These tracers are then subjected to advection, convection and vertical diffusion. These transport processes are calculated separately using an operator splitting method. In ECHAM5, advective transport is done first, followed by vertical diffusion, chemical reactions or exponential decay, and in a last step convective transport. Each transport process is calculated from the knowledge of the tracer concentration at the preceding time step except the convection in which the tracer concentration updated by the previous processes is used. The resulting tendencies of each single process are added to the concentration of the previous time step. This operator splitting is different from the classical strang splitting which was discussed in Lanser and Verwer (1999).

2.2 Experiment description

We consider nine independent idealized tracers each constrained to have constant mass mixing ratio of 1 in their respective source regions (see Fig. 1). This is equivalent

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to prescribing a source which is proportional to the temporally varying outflow from the region.

Horizontally, we divide the earth surface into three equal-area latitude bands called “north” (N), “tropics” (T) and “south” (S), following [Bowman and Carrie \(2001\)](#); [Bowman and Erukhimova \(2004\)](#). “North” refers to the region north of 19° N, the region south of 19° S is “south” and the region in the latitude bands in-between 19° N and 19° S is “tropics”. Vertically we introduce the tracers at three different altitude regimes (i.e. “surface”, “tropopause” and “stratosphere”). The “surface” tracers have their source at the lowest model level. The “tropopause” tracers have their source in the tropopause region, which is assumed to correspond to model levels at 100 hPa in the T region and 200 hPa elsewhere. The “stratosphere” tracers have their source at the model level that corresponds to 30 hPa, which is the second level in the vertical resolutions L19 and L31 used in the simulations. Henceforth, we will abbreviate the tracer names by combining their vertical and horizontal source region names; for example surfT is the surface tracer with source region in the tropics, while tropN stands for the tracer which is kept at constant concentration in the Northern-Hemisphere tropopause region (see Fig. 1). All tracers decay with a fixed globally uniform lifetime which is normally 5 months.

The experiments in this study are performed using a setup similar to the Atmospheric Model Intercomparison Project 2 (AMIP2, [Gates et al., 1999](#)) with prescribed sea surface temperatures and sea ice climatologies of the 1990s. Experiments to test the resolution dependency of tracer transport were performed in the resolutions T21L19, T42L19, T42L31, T63L31, and T106L31. The simulations were run in each resolution for 5 years including 1-year spin-up time.

Additional sensitivity experiments were performed to test the influence of ERA40 meteorology (run T63L31-era40, using 5 months tracer lifetime) and to demonstrate the influence of the tracer lifetimes. The latter runs were performed in T63L31 resolution with tracer lifetimes of 0.5 and 50 months, respectively. With a longer tracer lifetime, the model takes longer to reach a quasi steady state. Therefore, the 50 months lifetime experiment was run for a total of 13 years, of which we analyse the last 4 years.

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The inter-hemispheric exchange time was investigated in experiments with tracers of infinite lifetime. Thus, we assure that the tracers are not destroyed before they reach the other hemisphere.

3 The influence of model resolution on the global transport characteristics

5 The objective of this section is to characterise the resolution dependency of the export flux of tracer from its source region i into the global atmosphere. Across all the resolutions, the tracer lifetime τ is set as 5 months, which roughly corresponds to the lifetime of CO in the troposphere.

10 For any given tracer with source in region i and resolution r , the rate of change of the global mass $M_{i,r}$ is given by:

$$\dot{M}_{i,r}(t) = S_{i,r}(t) - \frac{M_{i,r}(t)}{\tau} \quad (1)$$

where $S_{i,r}$ is the time dependent mass flux out of the source region i in the resolution r .

15 According to our simulation setup, at $t=0$, $M_{i,r}(0)$ equals the mass of the tracer in the source region. This implies that $M_{i,r}(0)$ is proportional to the source region volume, because the tracer is uniformly distributed in the source region. The volume of the source region depends on the exact location of the grid box boundaries which demarcate the source region in each model resolution. Consequently, for each model resolution r , we normalise the quantities in Eq. (1) by dividing them with $M_{i,r}(0)$. With
20 $m_{i,r}=M_{i,r}/M_{i,r}(0)$ and $s_{i,r}=S_{i,r}/M_{i,r}(0)$, we get:

$$\dot{m}_{i,r}(t) = s_{i,r}(t) - \frac{m_{i,r}(t)}{\tau} \quad (2)$$

We further divide $m_{i,r}$ by $\hat{m}_{i,T63L31}$, which is the 4-year average of $m_{i,T63L31}$, to derive

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a comparison index, $R_{i,r}$:

$$R_{i,r}(t) = \frac{m_{i,r}(t)}{\hat{m}_{i,T63L31}} \quad (3)$$

Figure 2 displays the monthly mean values of $R_{i,r}$ across the model resolutions. Figure 2 shows that most of the simulations reached a quasi steady state over the last 4-year period. Therefore the integration of the left hand side of Eq. (2) over the last 4 years of the simulations yields:

$$\int_{4 \text{ years}} \dot{m}_{i,r}(t) dt = 0 \quad (4)$$

This results in:

$$\bar{s}_{i,r}(t) = \frac{\bar{m}_{i,r}(t)}{\tau} \quad (5)$$

where the bar indicates the 4-year average. This implies that the average export flux from source region i in resolution r is proportional to the global mass of tracer i in the quasi steady state. Therefore the order of the curves in Fig. 2 directly corresponds to the strength of the export fluxes in the respective model resolution.

The $R_{i,r}$ values of the tropopause and surface tracers in the 19-level (L19) (i.e. T21L19 and T42L19) experiments lie below the curves of the 31-level (L31) runs. Generally, there appears to be little influence of the horizontal resolution on global characteristics of tracer transport. A notable exception is the surfT tracer, which exhibits different values in the T21L19 and the T42L19 resolutions. To a lesser extent, the T106L31 resolution yields a larger $R_{i,r}$ values than other 31-level simulations for the surfN and surfS tracers. The largest differences between the L19 and L31 resolutions are found in the tropopause tracers. This can be explained by the position of the source regions relative to the tropopause.

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Some of the tracers (i.e. stratS, stratT, stratN, surfS, and surfN) show a distinct seasonal variation in all model resolutions, while others (i.e. tropS, tropN and surfT) exhibit only little variability. The tropT tracer has the least regular pattern, and it appears to follow a six-monthly seasonal cycle.

The relaxation of the atmospheric dynamics of the model to ERA40 data (i.e. run T63L31-era40) yields values of $R_{i,r}$ which is about 10% higher for the stratosphere tracers and about 10–15% lower for the tropopause tracers. The surface tracers exhibit relatively small differences compared to the AMIP2 T63L31 simulation. In addition, the T63L31-era40 run exhibits the Quasi Biennial Oscillation (QBO) in the stratT tracer. The presence of a QBO in this simulation is a consequence of the data assimilation procedure used to generate the ERA40 data. The ECHAM5 model, as used for our experiments does not resolve the stratosphere and hence cannot simulate the QBO, which could only be generated in the middle atmosphere ECHAM5 (MAECHAM5) model (Giorgetta et al., 2006).

An important feature for the application of the ECHAM5 model to chemistry transport simulations (e.g. Aghedo et al., 2007) is the fact that there is little difference in the transport between the T42L31 and the finer T63L31 resolution. This is in contrast to Roeckner et al. (2006) who found an improvement of the zonal mean climate state for increased horizontal resolution, but little change between T42L19 and T42L31.

4 Source-receptor relationships

Table 1 lists the fraction of tracer mass exported from source region i into the atmospheric column of the receptor regions S, T, and N in quasi steady state. It shows that the mean meridional transport of the surface and the tropopause tracers decreases in the coarse resolution models, except for the advection into the tropical region. This is a consequence of increased vertical mixing and recirculation in the coarse resolution models (see discussion on Table 2 below). However, a coarser model resolution leads to an increase in the inter-hemispheric transport in the stratosphere (see Table 1), with

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the exception of stratT tracer transported into S region.

Constraining the model with ERA40 data generally lead to a small change of about 1–3% in the inter-hemispheric exchange of surface and tropopause tracers. In contrast to its influence at the surface and the tropopause, ERA40 data increases the inter-hemispheric transport in the stratosphere; this increase is about 9–15% for transport from the tropical region to both hemispheres and about 100% for long-range exchange between the N and S regions. The QBO generated in the T63L31-era40 simulation may have contributed to this high inter-hemispheric mass exchange observed in the stratosphere tracers.

Table 1 also shows that the long-range inter-hemispheric exchange between the Northern and the Southern Hemisphere, and the inter-hemispheric transport of stratosphere tracers are most sensitive to the tracer lifetime. The largest differences occur between the tracers of 15 days and 5 months lifetime. The 50 months surface and tropopause tracers are well mixed, therefore the distribution within the regions varies by less than 7%, whereas this variation in the stratosphere tracers is up to 30%.

The cross tropopause transport of trace species plays a role for the budgets of various trace gases like ozone and halocarbons. As a proxy for cross tropopause transport, we consider the transport of the surface tracers to the stratosphere (i.e. the percentage of surface tracers found above the 50 hPa level) and transport of the stratosphere tracers to below 750 hPa (Table 2). The vertical transport of the tracers shows a dependence on the number of vertical levels, and models with fewer vertical levels show larger vertical transport. The percentage amount of tropical surface tracer transported to the stratosphere is slightly higher than that transported from its corresponding N and S region, due to the influence of convection in the tropics. Also slightly higher vertical exchange is observed in the NH compared to the SH due to orographic effects.

Although ERA40 data have little effect on the vertical mixing of the surface tracers within the troposphere, it increases their vertical transport to the stratosphere by about a factor of 2.5 (Table 2). ERA40 data also increase the transport of stratosphere tracers to below 750 hPa by up to 70%. This is consistent with findings of

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Van Noije et al. (2004), who investigated the sensitivity of stratosphere-to-troposphere exchange towards different meteorological forcing conditions in their chemistry transport model.

Owing to the long residence time of air in the stratosphere relative to our chosen lifetimes, the fraction of the mass exchanged between the stratosphere and the troposphere tends to 0 when the lifetime is short (0.5 month). The fraction of the surface tracers transported to above 50 hPa and stratosphere tracers transported to below 750 hPa rises respectively to about 0.4% and 1% when the lifetime is increased to 5 months, and to 4% and 15% when the lifetime increases to 50 months.

5 Inter-hemispheric transport time

In this section, we calculate the inter-hemispheric transport time between the Northern and Southern Hemispheres, by setting the boundary at the equator. This may be physically interpreted to represent the inter-tropical convergence zone (ITCZ) at the equator which acts as a major resistance to air mass exchange between Northern and Southern Hemispheres.

We use a conceptual two box-model, with one of the boxes containing the tracer source s as shown in Fig. 3. For each box $i=1, 2$, we denote the mass of tracer in the respective box by m_i . The decay rate of a tracer in box i is $\alpha_i=1/\tau_i$, where τ_i is the tracer lifetime. The transition rate of any tracer from box i to box j , $i \neq j$ is $\phi_{ij}=1/\tau_{ij}$, where $i, j=1, 2$. For this general setting, the kinetic equations for the tracer mass are as follows:

$$\dot{m}_1 = -\alpha_1 m_1 - \phi_{12} m_1 + \phi_{21} m_2 + s \quad (6)$$

$$\dot{m}_2 = -\alpha_2 m_2 - \phi_{21} m_2 + \phi_{12} m_1 \quad (7)$$

If a tracer with an infinite lifetime and no source (i.e. $\alpha_1=\alpha_2=0$, and $s=0$) attains a spatially uniform distribution in the steady state, it can be shown that $\phi_{12}=\phi_{21}=\phi$. If the tracer is not in the steady state (which means that either $s \neq 0$ or the tracer has

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a non-uniform distribution), we can calculate the seasonality of the inter-hemispheric transport time $\tau_{ex}=1/\phi$ from Eq. (7), noting that $\alpha=0$ when the tracer has infinite life-time:

$$\tau_{ex} = \frac{m_1 - m_2}{\dot{m}_2} \quad (8)$$

5 This is the equation of Prather et al. (1987), which was also used by Kjellström et al. (2000) to determine the inter-hemispheric transport time from simulated SF₆ concentrations.

Figure 4 shows the results of the inter-hemispheric transport time calculated using surfN and surfS tracers in the model resolutions T21L19, T42L19, T42L31, T63L31, and the T63L31-era40 version. The minima of the exchange time occur in the months of December to January and June to July. During these months, the exchange of the air masses across the equator is particularly active and the transport times for tracers in both directions are low. This cycle is connected to the position of the ITCZ, which migrates to the north and south of the equator in July–August and January–February respectively, thereby allowing the air masses to easily cross the equator. Furthermore, the more rapid the location of the ITCZ changes, the more intense is the associated exchange of air masses between the large scale northern and southern convective systems.

Figure 4 also shows that the inter-hemispheric exchange times of the finer resolution models in the AMIP2 runs are 1–2 months lower than those of the coarse resolution models and T63L31-era40 simulation.

The annual mean values of the inter-hemispheric transport time across various model resolutions are given in Table 3. These results are lower than the inter-hemispheric exchange time of 1.5–1.7 years calculated from ⁸⁵Kr concentrations by Levin and Heshaimer (1996) with the use of a different two-box model. They explain however, that their result may overestimate the real inter-hemispheric transport time because the interpolation of observation data neglects a decrease in concentration towards higher altitudes and in the stratosphere. We remark that the inter-hemispheric

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exchange time of 1.14 ± 0.16 yr estimated by Czeplak and Junge (1974) is shorter than the exchange time of Levin and Heshshaimer (1996) but still higher than our 0.60 to 0.74 years. Our new results for ECHAM5 are very similar to the seasonal variation of the inter-hemispheric exchange time calculated with ECHAM4 by Kjellström et al. (2000).

5 An analysis of the cross tropopause transport time is not possible within this study, due to the wide range of transport time scales in the stratosphere and for the stratosphere-troposphere exchange.

6 Summary and conclusions

The influence of model resolution, ERA40 meteorology and the lifetime on the transport of tracers in ECHAM5 has been examined using 9 tracers defined at different horizontal and vertical regions. Generally, transport is more vigorous in the finer resolution models and are mostly dependent on the number of vertical levels. The T42L31 resolution yields similar transport to other L31 simulations.

15 We found a decrease in the inter-hemispheric transport of surface and tropopause tracers in the coarse resolution models due to an increase in the vertical mixing and recirculation within the source region. However, a coarse model resolution leads to enhanced inter-hemispheric transport in the stratosphere. The use of ERA40 data only slightly affects the inter-hemispheric transport of surface and tropopause tracers, whereas it increases the inter-hemispheric and vertical transport of tracers in the strato-
20 sphere by up to 100%, and a factor of 2.5, respectively. The use of ERA40 data also show the effect of Quasi-Biennial Oscillation on transport at the tropical stratosphere.

The long-range inter-hemispheric transport between the Northern and the Southern Hemisphere, and the inter-hemispheric transport of the stratosphere tracers are most affected by the tracers' lifetime. The largest differences are however found between the tracers with lifetime of 0.5 month and 5 months. The 50 months surface and tropopause tracers are well mixed, therefore the distribution within the regions vary by less than 7%, and the percentage amount found in our 3-latitudinal regions is between 30–36% irrespective of their source region. Tracer lifetime also has a strong influence on the

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seasonal cycle of the tracers.

The interpretation of the simulation results with a conceptual box model shows that it will take about 7 to 9 months for the surface tracer with source in the Southern and Northern Hemisphere respectively to be transported to the other hemisphere. These results are lower than the inter-hemispheric exchange time of 1.5–1.7 years calculated from ⁸⁵Kr concentration by Levin and Heshshaimer (1996) with the use of a different two box model. The inter-hemispheric transport is most active in December to January and June to July. The finer resolution models in the AMIP2 runs yield a seasonal cycle of the inter-hemispheric exchange times, which are 1–2 months lower than those of the coarse resolution models and T63L31-era40 simulation.

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Table 1. The amount of tracers found in the three regions – N, T and S, for all simulations (in %) at quasi steady state. Note that there are no stratosphere tracers included in the T106L31 resolution due to computational cost.

Tracers and receptor region	T21L19	Resolutions (5 months lifetime)				Meteorology (5 months lifetime)		Lifetime (T63L31)	
		T42L19	T42L31	T63L31	T106L31	T63L31-era40		0.5 month	50 months
Surface tracers									
surfN to S	12.3	13.5	15.7	16.3	15.9	15.2		1.2	30.8
surfS to N	12.7	13.9	15.9	16.6	16.0	15.5		1.5	30.7
surfN to T	34.9	31.2	31.8	30.8	31.3	30.7		18.3	32.6
surfS to T	34.9	32.3	32.6	31.4	32.3	32.0		19.2	32.8
surfT to N	25.6	26.8	27.6	28.4	27.8	27.8		14.8	32.9
surfT to S	26.4	28.0	28.5	29.1	29.0	28.5		15.2	33.2
Tropopause tracers									
tropN to S	15.1	15.4	18.4	18.9	18.2	17.4		2.6	31.3
tropS to N	15.1	15.4	17.9	18.4	17.4	16.5		2.3	31.1
tropN to T	40.1	34.6	36.3	34.8	34.2	34.4		30.8	33.1
tropS to T	41.3	36.4	37.3	35.7	36.1	34.9		32.5	33.2
tropT to N	28.3	30.8	30.0	31.3	30.7	32.4		20.2	33.3
tropT to S	26.5	30.0	30.2	31.0	31.0	31.7		20.6	33.6
Stratosphere tracers									
stratN to S	2.8	2.2	2.3	2.3	—	5.9		0.01	22.3
stratS to N	3.2	2.8	2.4	1.9	—	3.8		0.01	21.5
stratN to T	20.8	16.1	16.4	15.1	—	15.5		6.7	26.4
stratS to T	21.3	17.1	16.7	14.5	—	14.2		6.8	25.9
stratT to N	26.5	25.9	24.0	24.6	—	28.3		8.2	33.9
stratT to S	24.9	25.0	26.1	27.0	—	29.5		8.8	35.5
Tracers remaining in the source region									
surfN in N	52.8	55.3	52.5	52.9	52.8	54.1		80.5	36.6
surfS in S	52.4	53.8	51.5	52.0	51.7	52.5		79.3	36.5
surfT in T	48.0	45.2	43.9	42.5	43.2	43.7		70.0	33.9
tropN in N	44.8	50.0	45.3	46.3	46.6	48.2		66.6	35.6
tropS in S	43.5	48.2	44.8	45.9	46.5	48.6		65.2	35.7
tropT in T	45.2	39.2	39.8	37.7	38.3	35.9		59.2	33.1
stratN in N	76.4	81.7	81.3	82.6	—	78.6		93.3	51.3
stratS in S	75.5	80.1	80.9	83.6	—	82.0		93.2	52.6
stratT in T	48.6	49.1	49.9	48.4	—	42.2		83.0	30.6

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Table 2. Fraction (in %, with respect to global tracer mass) of tracer mass exported from various source regions into the atmosphere above 50 hPa and below 750 hPa. Note that there are no stratosphere tracers included in the T106L31 resolution due to computational cost.

	Resolutions (5 months lifetime)					Meteorology (5 months lifetime)	Lifetime (T63L31)	
	T21L19	T42L19	T42L31	T63L31	T106L31	T63L31-era40	15 days	50 months
surface tracers above 50 hPa								
surfN	0.54	0.63	0.39	0.38	0.37	0.92	0.0057	3.68
surfT	0.65	0.72	0.47	0.43	0.39	1.14	0.0124	3.74
surfS	0.46	0.54	0.35	0.33	0.32	0.81	0.0042	3.63
Stratosphere tracers below 750 hPa								
stratN	1.47	1.80	1.32	1.35	–	2.04	0.0004	15.63
stratT	0.95	0.90	0.76	0.89	–	1.19	0.0008	14.04
stratS	1.05	1.16	1.07	1.11	–	1.78	0.0003	15.32

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Table 3. Annual mean value of the inter-hemispheric transport time τ_{ex} (in months) of the surfN and surfS tracers in various model resolutions.

	surfN	surfS
T21L19	8.6	8.9
T42L19	8.8	8.5
T42L31	7.6	7.4
T63L31	7.3	7.2
T63L31-era40	8.5	8.3

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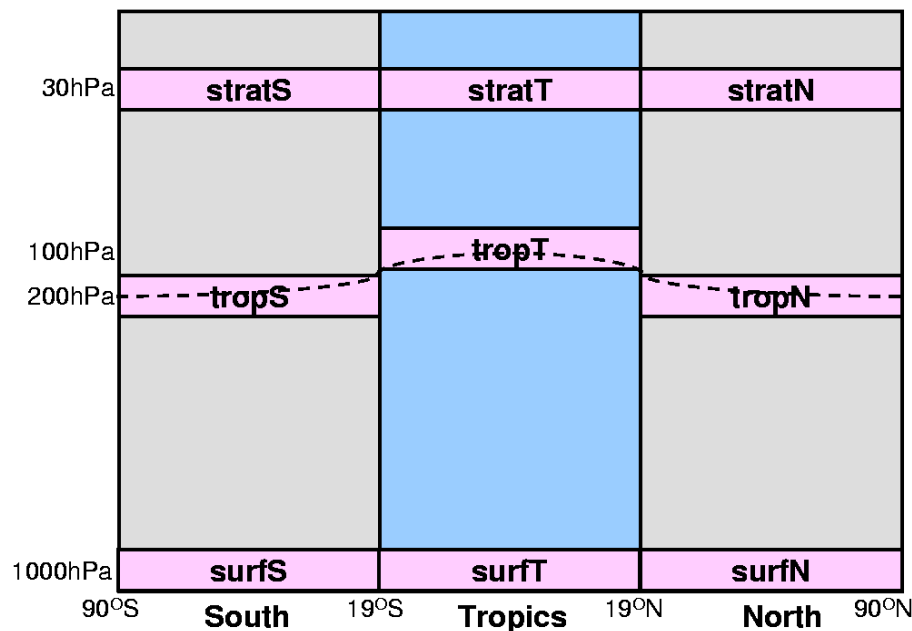


Fig. 1. Schematic diagram showing the independent idealized tracer source regions. The dashed line is the tropopause, while the gray shaded parts are the “north” (N) and “south” (S) regions. The blue shaded region is the “tropics” (T). The surface tracers (surfN, surfT and surfS) are introduced at the lowest model level, while the stratosphere tracers (stratN, stratT and stratS) are emitted at 30 hPa level. The tropopause tracers are released at 100 hPa and 200 hPa for tropT and tropN (or tropS) respectively. Note that the diagram is not drawn to scale.

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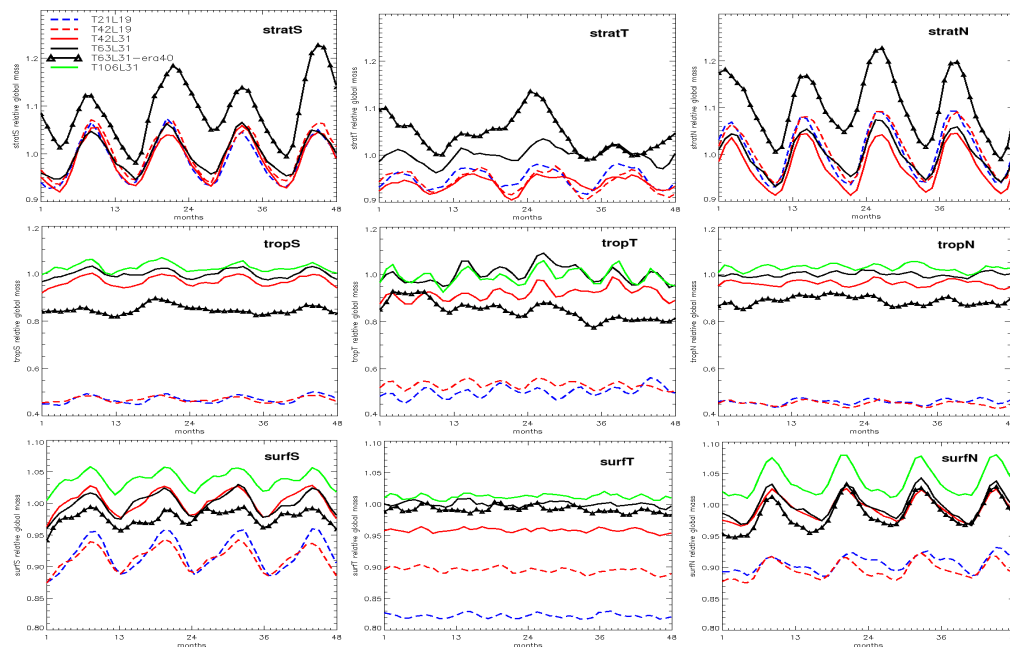


Fig. 2. $R_{i,r} = m_{i,r} / m_{i,T63L31}$ for $r = T21L19, T42L19, T42L31, T63L31, T63L31\text{-era40}$ and $T106L31$. Note that there are no stratosphere tracers included in the $T106L31$ resolution due to computational cost.

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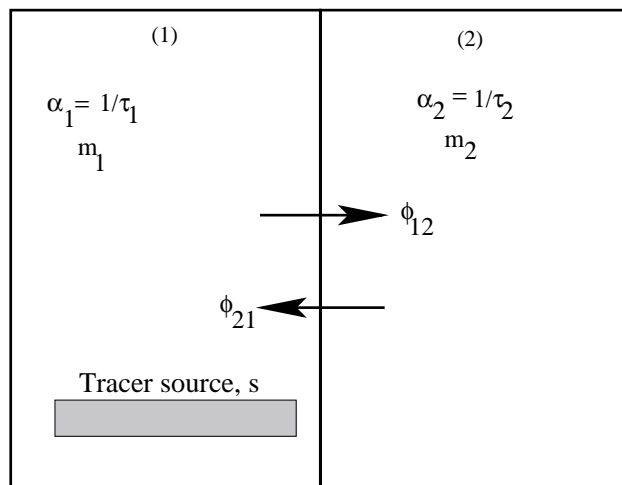


Fig. 3. Conceptual model of tracer transport. See text for details and the description of the parameters.

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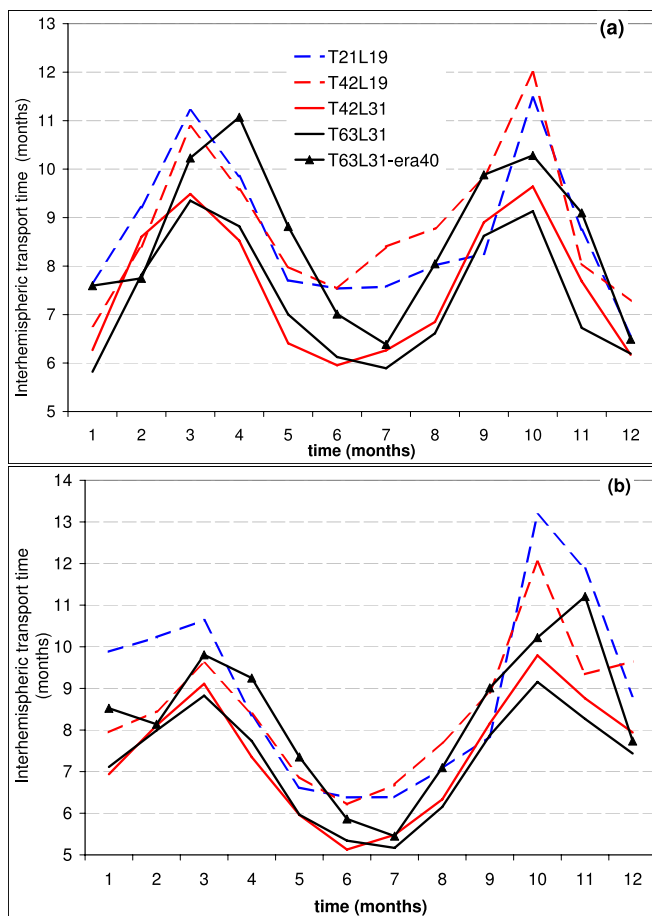


Fig. 4. Transport time τ of the surfN (a) and surfS (b) tracer for different model resolutions.

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